DESIGNING A GENETIC-BASED FLC FOR FAST ATTITUDE CONTROL OF SATELLITES WITH REACTION WHEELS

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ABSTRACT

In this paper, a systematic technique is proposed to design an optimal fuzzy logic controller (FLC) for the fast attitude control of satellites with reaction wheels. The optimization is performed by generating the rules and the distribution of membership functions of the FLC using the genetic algorithm. To get accurate pointing, long life time, and fast response for the satellite, the deviation of the satellite from its nominal position, the consumed power, and the time of deviation are included in the optimization objective function.

Index Terms— Fuzzy, Genetic algorithm, Satellite

1. INTRODUCTION

The satellite carries on board different equipment for remote sensing and telemetry which needs to be precisely pointed to the earth. The satellite may receive an impulsive torque from any particles moving in the space which results in deviation of the satellite from its attitude. This deviation will result in a poor imaging and communications with the ground stations. An attitude control must used to return the satellite back to its orientation [1].

An extensive research was done to control the attitude of the satellites using classical control techniques [9]. However these types of controllers have a limited capability and they are usually linear and require an accurate model. The fuzzy logic control (FLC) is well known of its robustness, suitability for handling linear and non-linear model, ability to handle imprecise knowledge and ill defined system [8].

The core of FLC is the rules which determine the relation between the inputs and the output. Usually these rules are obtained by mapping the performance of a skillful operator or from an engineering experience about the dynamics of the system. The generated rules from these methods are not available in satellite operations. Self organizing FLC can be used for generating the rules which is more robust than the fixed rules controller but it is not necessarily to be optimum [4]. Therefore, we propose in this paper a systematic technique to design an optimal FLC for controlling the attitude of the three-axis stabilized satellite controlled by reaction wheels (RWs). The FLC rules and membership function parameters are determined based on solving an optimization problem using the genetic algorithm (GA). To increase the life time of the satellite and its pointing accuracy, we include the consumed power, the deviation of the satellite from its nominal position, and the time of deviation in the objective function.

GA is a random search and optimization technique, but it is guided towards better performance through the selection mechanism. Contrary to the regular search algorithms, it does not deal with one solution, but a set of solutions called a population. Each solution in the population is called an individual which is encoded representation of all the parameters in the solution. GA employs so-called "genetic operators" to create new individuals from the existing ones by merging (crossover operation) or modifying (mutation operation) the existence individuals. The new individuals replace the old ones and through this process the population will converge to a best solution. GA optimize a performance index based on input/output relationships only, therefore, minimal knowledge of the plant under investigation is required.. In addition, because derivative information is not needed in the execution of the algorithm, many pitfalls that gradient search methods suffer can be overcome [5]. Also, because the GA do not need an explicit mathematical relationship between the performance of the system and the search update, the GA offer a more general optimization methodology than conventional analytical techniques [6].

2. SATELLITE DYNAMICS

If the satellite receives a disturbance torque T_d , it will be deviated from its nominal desired orientation. To return it back, a reaction wheel is rotated by applying a voltage e to a DC motor, Figure 1. This makes the unwanted torque be translated from the satellite into the reaction wheel. This is called fast attitude control since the bandwidth of the system is larger than the orbital rate of the satellite. In this case, the rotational motions of the satellite about its principal axes are decoupled. Hence, three orthogonal reaction wheels are needed to control the satellites. The equations of motion of a satellite with reaction wheels are presented in details in Bryson [1]. Here, we recall the normalized equations of motion about the pitch axis which can be written as (roll and yaw are similar),

$$\dot{\theta} = \overline{q}$$
$$\dot{\overline{q}} = -\overline{q} + \frac{\overline{H}}{(1+\varepsilon)} + \overline{e} + \overline{T}_d \qquad (1)$$
$$\dot{\overline{H}} = \overline{T}_d$$
$$\overline{H} = \overline{q} + \varepsilon \overline{q}_w$$

where $\overline{H}$ is the normalized total momentum of the satellite and the reaction wheel

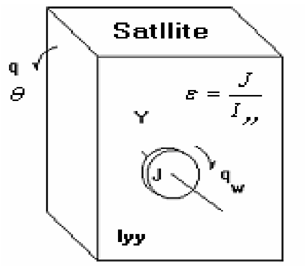


Figure 1 Configuration of the satellite with RW

Using the disturbance rejection, let

$$\delta e = \overline{e} + \frac{\overline{H}}{1+\varepsilon} \qquad (2)$$

In the case of impulse disturbance torque, the equations reduces to

$$\begin{bmatrix} \dot{\theta} \\ \dot{\overline{q}} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} \theta \\ \overline{q} \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \delta e \qquad (3)$$

with $\overline{q}(0) = \overline{T}_{dy}$

3. CONTROLLER DESIGN

The structure of the proposed attitude controller is shown in Figure 2. The FLC has two inputs; the satellite pitch angle and the normalized pitch angle rate while the output is the voltage sent to the motor to drive the reaction wheel.
The fuzzy controller received crisp data from the satellite sensors and converts these data into fuzzy variables which is called fuzzification process. The fuzzified data go through a set of if-then rules in an inference engine and result in some fuzzy outputs which are converted back to a crisp value through a process called defuzification by the weighted average method.
The first step in the design of the FLC is to choose the number and distribution of membership functions (MF's) for the inputs and the output. In this work, seven normalized membership functions with triangular shapes are considered, Figure 3. However, the same procedure can be used for any other functions.

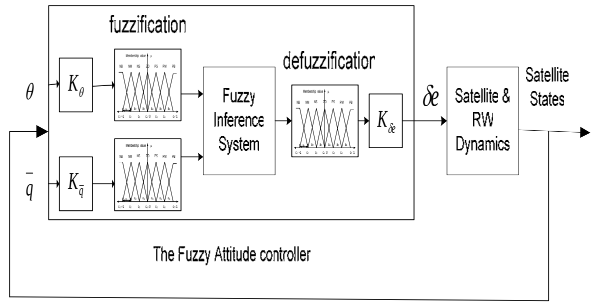


Figure 2 Structure of the satellite attitude fuzzy controller

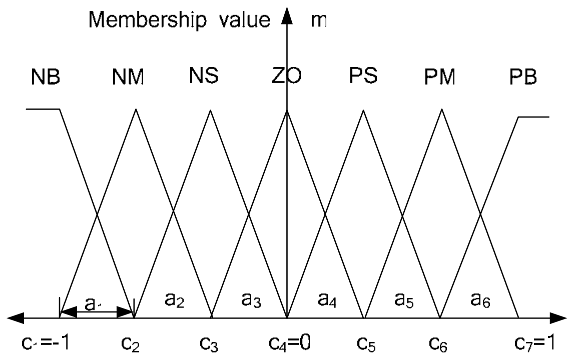


Figure 3: The normalized membership functions

To describe these functions, we need to determine the location of the triangles vertices, only four are needed in our case (i.e. c_2, c_3, c_5, and c_6) with the following constraints

$$-1 \prec c_2 \prec c_3, \quad c2 \prec c_3 \prec 0$$
$$0 \prec c_5 \prec c_6, \quad c_5 \prec c_6 \prec 1 \qquad (4)$$

These constrains complicate the optimization process since they will be added in the optimization objective function as a penalty. To overcome this problem, the ratio of the distances between these centers will be used instead of the vertices locations. The values of these distances should be positive and there are no constraints among them except that the summation of the distances in the negative or positive side is unity. In this case, the vertices locations can be determined as following

$$w_1 = \frac{1}{\sum_{i=1}^{3} a_i}, \qquad c_{i+1} = c_i + w_1\, a_i, \qquad i = 1,2$$
$$w_2 = \frac{1}{\sum_{i=4}^{6} a_i} \qquad c_{i+1} = c_i + w_2\, a_i, \qquad i = 4,5 \tag{5}$$

Since the ranges of the membership functions are normalized, scaling factors are used to transform these normalized ranges to the physical operating ranges. If we assume that the maximum allowed pitch angle, normalized disturbance torque and normalized motor voltage are $\theta_{\max}$, $\bar{T}_{d\max}$, and $\delta\bar{e}_{\max}$ respectively, then the corresponding scaling factors are determined as

$$K_\theta = \frac{1}{\theta_{\max}}, K_{\bar{q}} = \frac{1}{\bar{T}_{d\max}}, K_e = \delta e_{\max} \tag{6}$$

For an FLC with two inputs and *n* membership functions for each input, there are n^2 rules which should be chosen. The consequent of each rule can take any of the output fuzzy variables. To able to include the linguistic rules in the optimization process, we use integer encoding system to refer to the output fuzzy variables a shown in Table 1.

Table 1: The encoding system for the FLC output

MF	NB	NM	NS	ZO	PS	PM	PB
Code	1	2	3	4	5	6	7

4. FORMULATION OF THE OPTIMIZATION PROBLEM

Now, our goal is to find the consequents of the FLC rules and the membership functions parameters such that the performance of the satellite is optimum according to a chosen objective function. In this work, we choose to minimize the objective function shown in Eq (7) which include the history of the pitch angle, the consumed power, and the total time (tf) which is needed to return back the satellite to its nominal position.

$$f = \int_0^{t_f} \left(w_1\theta^2 + w_2 u^2 \right) dt + w_3 t_f \tag{7}$$

The optimization problem can be formulated as

$$\min f(z) \qquad z \in R^{68} \tag{8}$$

Subjected to

$$\theta = \bar{q} = 0 \qquad at \qquad \bar{t} = t_f$$

Where:

z is a vector contains the solution parameters
w's are the objective weights which determine the relative importance of each term in the objective functions; these weights are positive and should be chosen properly.

GA is used to solve the above constrained problem to find the best solution or individual according to the GA terminology. In this problem, the solution contains two types of data: integers and real numbers, Figure (4). Therefore, each individual in the GA population is constructed of two different segments: the first one contains 49 integers for the fuzzy rules where integer mutation and crossover operations will be applied; the second segment contains 19 real numbers for the parameters of the membership function and the final time where real crossover and mutation will be applied. However, the selection process will be applied for the individual as a whole.

$$z = \{ \overbrace{\overbrace{r_1, r_2, .. r_{49}}^{Rules}}^{Integer} \,|\, \overbrace{\overbrace{a_1, a_2, .. a_6}^{MF\ for\ \theta}, \overbrace{a_1, a_2, .. a_6}^{MF\ for\ \bar{q}}, \overbrace{a_1, a_2, .. a_6}^{MF\ for\ \delta\bar{e}}, t_f}^{Real} \}$$

Figure 4: Structure of the GA individual

The optimization problem in Eq (8) contains constraints which complicate the optimization process. Therefore, many techniques were proposed to handle these constraints in GA. The most common technique is the method of penalty function. With this method, the constraint optimization problem is transformed into a non-constrained one by augmenting of the original objective function *f* with a penalty function *P*. Many researchers proposed different forms for the penalty functions [3]. In this work, we define *P* with two levels depending on the magnitude of the violation of the constraints. This proposed structure for the penalty function allows the individuals that slightly violate the constrains to get higher fitness compared with that ones with high viloation which is shown to be a good approach to move to the best possible solution.

To define such levels it demands to define intervals for each of the violation and a penalty value for every interval as following:

$$P_o = k_1 \left|\theta(t_f)\right| + k_2 \left|\bar{q}(t_f)\right| \tag{8}$$

$$P(z) = \begin{cases} P_o & 0 \le \theta(t_f) \le \theta_{\max}/4 \\ K\,P_o & \theta(t_f) \succ \theta_{\max}/4 \end{cases}$$

Where k's are large constant compared with the weighing factors. These k's are chosen such that no of the constraints is dominating. K is also a large constant which is chosen to insure that high non-feasible individuals are discarded from the population.

4.1. Calculation of the objective function

If single initial condition or scenario is used to determine the objective function, the GA can produce a controller that works well around this operating condition while it may fail elsewhere. To able to find a satisfactory controller which operates over the entire range of the input spaces, we choose multiple initial condition which are a combination of ($\theta_{\max}$, $\bar{q}_{\max}$, and 0). Therefore, the total value of the objective function is the sum of the objective functions from all the initial conditions [7].

5. RESULTS

In this work, we chose

$$\theta_{\max} = 30^o, \bar{q}_{\max} = T_{d\max} = 1.0, \delta e_{\max} = 1.3$$

with the following constants for the objective and penalty functions.

$$w_1 = w_2 = w_3 = 1; k_1 = 200, k_2 = 100, K = 100$$

The GA Toolbox developed by Chiperfield et. al. [2] was used to implement the proposed algorithm. The GA algorithm is executed according the flow diagram shown in Figure 5. The values used for the GA parameters are: 50 for population size, 0.7 for crossover rate, and 0.01 for mutation rate. Linear ranking with the method of roulette wheel are used to select the individuals who produce the offsprings that joined the next generation.

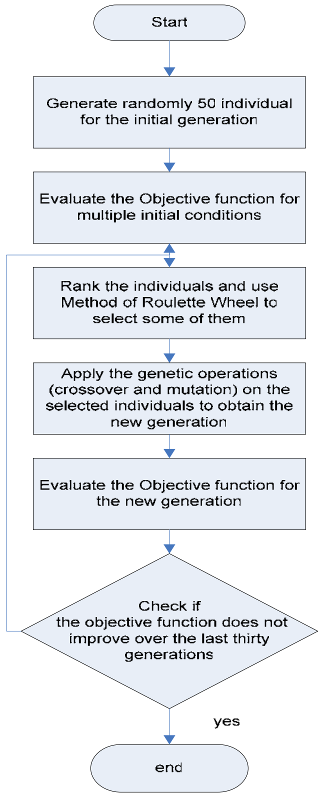


Figure 5: Flow chart of the GA algorithm

The best objective function and final time in each generation are shown in Figure 1 while the final optimized rules and membership function distribution are shown in Table 2 and Figure 7 respectively. The time history of satellites states due to two different initial conditions are shown in Figure 8. It is clear from these results that the proposed algorithm was able to generate an optimal FLC with a satisfactory performance.

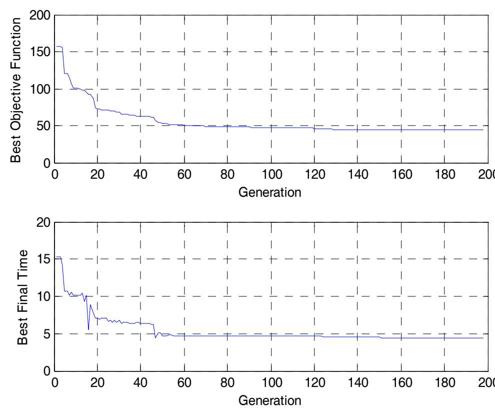


Figure 6: The best objective function and final time in each generation

Table 2: The best generated rules

	δe	NB ($\bar{q}$)	NM	NS	ZO	PS	PM	PB
	NB	NS	NM	NB	NB	PB	PS	PS
	NM	NS	PM	ZO	NM	PS	ZO	PB
θ	NS	ZO	NB	NB	NM	PS	ZO	PM
	ZO	ZO	PS	NB	ZO	PM	PS	NB
	PS	PM	NB	NB	PS	PS	NM	NS
	PM	NM	NB	NB	PM	NS	ZO	ZO
	PB	PS	NB	PS	PB	PB	NS	NS

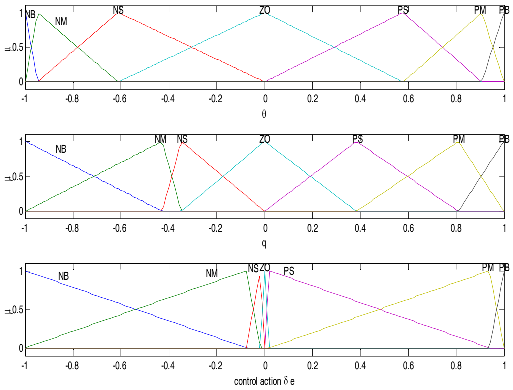
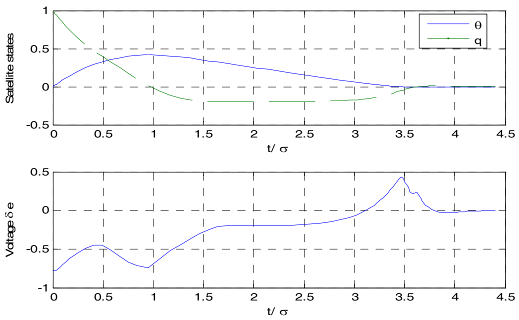
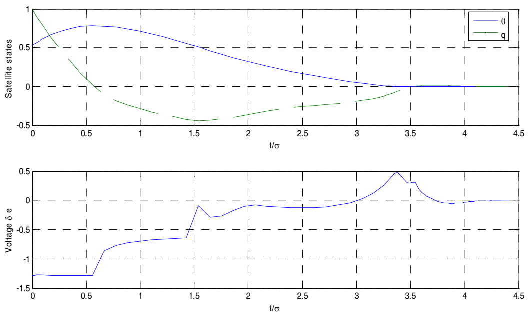


Figure 7: The best generated MF's



(a)



(b)

Figure 8: Response of the satellite with the designed FLC due to: (a) impulse torque (b) impulse torque with initial pitch angle

6. CONCLUSION

GA was successfully applied to generate the rules and the membership functions distribution for FLC which was successfully applied to control the attitude of a satellite with reaction wheel. With the use of multiple initial conditions in determining the objective function, the designed controller is shown to be stable in a broad range of the operating conditions.

7. ACKNOWLEDGEMENT

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